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# Strategic selection of suitable projects for hybrid solar-wind power generation systems

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ABSTRACT

Because of the pressing need for maintaining a healthy environment with reasonable costs, China is moving toward the trend for generating electricity from renewable resources. Both solar energy and wind power have received a tremendous attention from private associations, political groups, and electric power companies to generate power on a large scale. A drawback is their unpredictable nature and dependence on weather. Fortunately, the problems can be partially tackled by using the strengths of one source to overcome the weakness of the other. Especially, a large fraction of the solar resource is available at times of peak electrical load. However, the complexity of using two different resources together makes the hybrid solar-wind generation systems more difficult to analyze. Accordingly, this paper first briefly introduces the solar-wind generation system and next develops its critical success criteria. Then, a fuzzy analytic hierarchy process associated with benefits, opportunities, costs and risks, is proposed to help select a suitable solar-wind power generation project.


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## 1. Introduction

The combined effects of the depletion of fossil fuels and the gradually emerging consciousness about environmental degradation have given the first priority to the use of renewable alternative energy resources in the 21st century. The main advantages of renewable energy are the absence of harmful emissions and the conversion of infinite availability of renewable resources into electricity [1]. Environment-friendly renewable energies like hydraulic energy, wind energy, and solar energy have received increasing attention as alternative means of meeting global energy demands. Specifically, the rapid development in solar and wind energy technology has made it the most promising alternative to conventional energy systems in recent years [2,3].

In a single year in 2008, the global wind power industry installed a capacity of 27GW, 28.8% growth, and the cumulative global wind power capacity has grown to 120.8GW [4,5]. In China, with potential capacity of 250GW, the installed capacity of wind power was stably increased from 84, 90, 67, 93, 134, 756, 1.3GW, 5.9GW to 12.2GW for year 2000 through year 2008 [5,6]. In addition, the solar availability in China is excellent, with more than two-thirds of the areas having 2200 h of sunshine a year and an annual solar radiation exceeding 5860 MJ/m$^2$ [7]. In the attempt to encourage the installation of renewable and sustainable energy in

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China, Renewable Energy Law (REL), into force in January 2006, stipulated that renewable energy must contribute 10% of the national energy supply by year 2020 [8,9]. The REL is administrated by the National Development and Reform Commission (NDRC), and is implemented by governments at the regional and local levels. Nevertheless, decisions on regional targets will be based upon regional circumstances such as the availability of renewable energy [10].

It is foreseeable that the move to generating electricity through solar energy and wind power will attract private associations, political groups, and electric power companies to generate power on a large scale in recent years. A drawback of the two energy resources is the unpredictable nature and dependence on weather. Even though the problems can be partially confronted by using the strengths of one source to overcome the weakness of the other, the complexity of integrating these two resources together makes the hybrid solar-wind generation systems more difficult to analyze [11]. Some optimization techniques, such as graphical construction method [12], probabilistic approach [13], iterative technique [14], and genetic algorithm [11], have been applied to assess the economic feasibility of a hybrid solar-wind power generation project by benefit and cost analysis. However, there has not been any work that describes and analyzes such an important topic based on benefits, opportunities, costs and risks simultaneously. Therefore, this paper tries to analyze the critical success criteria and develop an integrated framework to help evaluate solar-wind power generation projects. In conventional analytic hierarchy process (AHP), pairwise comparison of relative criteria based on experts' opinions is applied to rank the final priority. However, synthesizing the positive criteria of benefits (B) and opportunities (O) and the negative criteria of costs (C) and risks (R) with rating calculation is a more comprehensive way to deal with such a complicated project [15–17]. In addition, experts' judgment is always imprecise and vague. To compensate the deficiencies and solve the aforementioned problem, a fuzzy AHP with BOCR is proposed to select a suitable solar-wind power generation project.

The rest of this paper is organized as follows. In Section 2, literature related to project evaluation and management is introduced. A hybrid solar-wind power generation system and its critical success criteria are discussed in Section 3. A fuzzy AHP model with BOCR for evaluating solar-wind power generation projects is constructed in Section 4, and a practical example is examined in Section 5. Some conclusions and discussions are provided in the last section.

## 2. Project evaluation and management

The project evaluation and management issues have been discussed and applied in various management functions, such as research and development [18], quality management [19], environmental energy management [20], etc. During the 1950s, planning techniques and network analysis such as PERT and CPM formed the focus of development in project management. In the 1960s, these techniques continued to be popular in the construction industry, but cost and scheduling control gained popularity within the defense and aerospace industries. In the 1970s, a focus on teamwork as a defining feature of project management and an emphasis on breakdown structures dominated the research in scholarly and pragmatic fields [21]. In the 1980s, the topics such as project organization, project risk, project front end, external influences to projects, and initial work on the development of project management standards were stressed in practical industry [9,22,23]. In the 1990s, with increasing risk uncertainty and limited resources, portfolio decisions became important because of the difficulty of allocating a scarce budget over multiple periods, multi-period consequences, and uncertain and often interdependent projects that compete for a common pool of resources [18]. Some authors made a comprehensive study on strategic intent of project, criteria for project selection, and various qualitative and quantitative project selection models [24]. Synthesis of results revealed that relationship management, resource management, time management, cost management and risk management all displayed consistent significance throughout the past 10 years [25]. In addition, project evaluation and improvement of strategic attainment were both increasing in their significance in the research on project management [26]. The review of literature also finds that project management is primarily based on a few critical factors, and that the emphasized critical factors have changed over time.

Because environmental regulations become stricter all over the world, such an impact implies that alternative sites, technologies, designs, and methods are thought as mitigating measures [27]. In fact, the situations faced by electricity companies have become more complex and riskier. In the past, relative security in electrical supply and in power price made fuel price and electric demand as the only uncertainties. However, the uncertain sources have been increased because of liberalization of electric markets. Today, variant risks such as increased volatility of fuel price, fast change of technologies and regulatory modification need to be considered when electricity companies make their investment decisions [28]. Feasibility analysis usually takes a longer time, and the implementation must wait until the statutory and regulatory authority approves the project. Specifically, because either environment-friendly alternative will always be non-economical or financial with technological analysis may eliminate better options, feasibility analysis through above processes often results in sub-optimal project.

Under these circumstances, finding an integrated framework for evaluating projects with regards to variant factors such as market, technologies, social and environmental impacts is very important for power companies. Then, strategic selection and operations of a solar-wind power generation project can be implemented successfully once its critical success criteria are fully understood (described in Section 3) and a method for solving multi-criteria decision-making problems is proposed (described in Section 4) in advance.

## 3. Hybrid solar-wind generation systems and their critical success criteria

In recent years, the developments of renewable energy, such as solar energy and wind power, have become very active because renewable energy not only reduces the consumption of petroleum and coal but also meets the general demand for balancing the economic development and environment protection [29]. The European Union (EU) aims to supply 22% of electricity demand from renewable energy sources by 2010 [30]. Legislation, recently passed in many states of U.S., requires that state energy companies provide between 25% and 30% of their power from renewable energies by 2020 [31]. In China, renewable energy aims to contribute 10% of the national energy supply by year 2020 [8]. Without doubt, renewable energy, especially solar energy and wind power, will play an important role in the 21st century.

A wind farm is a collection of wind turbines in the same location to generate wind-powered electricity. Individual turbines are interconnected with a medium-voltage collection system. This medium-voltage electricity is then stepped up with a transformer to a high voltage transmission system and an electric grid. The development in wind technology has resulted in wind turbine generators (WTG) that are relatively comparable to conventional units in terms of both cost and capacity ratings. Parameters like reliability, capacity factor, power factor, technical availability, and

real availability are important factors affecting the performance of WTG [32]. Variation of wind speed has an impact on the economics, duration of life, and smooth running of the wind energy conversion system. The annual behavior of wind speed provides basic information about the wind strength and consequently about the availability of wind power [33]. In order to study the long-term trend of mean wind speed, annual mean of the wind speed and wind power density need to be measured, calculated and analyzed [34,35]. Interconnection with electric networks, influence of selected height of installation above ground, effect of wind gusting and micro-siting of WEGs are also main influences of annual energy output [36]. In addition, wind farm investment costs should consist of the costs of foundation, costs of electrical connection, costs of grid connection, land purchase, planning costs, approvals, infrastructure, wind turbines, and management skills [20]. Switchable tariff provides option value in coordinating the seasonality of wind energy, demand on electric power and electricity price movement [37]. With recent developments in power electronic converters, variable speed generations seem to be feasible and cost effective [38,39]. Since October 12, 2005, China decided on some measures regulating the legal modalities of clean development mechanisms (CDM) implementation [40]. The wind power concession program auctions off wind power development rights including a guaranteed tariff and concession operation agreements [41]. Such on-grid tariff of wind power is decided by bidding. If the tariff is higher than the referenced on-grid tariff of desulfurized coal-fired power, the difference will be shared in the selling price at the provincial and national grid levels [41]. American Wind Energy Association (AWEA) lists the most important steps in building a wind farm: understanding wind resource, determining proximity to existing transmission lines, securing access to land, establishing access to capital, identifying reliable power purchaser or market, addressing site and project feasibility considerations, understanding wind energy's economics, obtaining zoning and expertise, establishing dialogue with turbine manufacturers, and securing agreement [42].

Solar-powered generation systems basically contain photovoltaic cells (PV) for the direct conversion of solar to electrical energy by solid state devices, solar–biological processes that produce fuels for operation of conventional engines, and concentrating solar power (CSP) systems that drive an electrical generator by utilizing mirrors to concentrate solar radiation to heat a fluid. In addition, there are three types of system architectures for CSP applications: the parabolic trough concentrator (PTC) system, the power tower system, and the dish system. The PTC system is often chosen because its efficiency is predicted to be the best among three CSP applications [43] and because it is the only type of solar thermal system with a long-operating history at utility scale at this time [31]. The major components of the PTC system are collectors, fluid transfer pumps, power generation systems and controls. The critical factors for the erection of PTC plants taken into account are the slope of the terrain, land use, geomorphologic features, hydrographical features, proximity to infrastructure, and solar irradiation of the area [2]. Commercial plants of 30 and 80 MW electric generating capacity are usually in operation for more than a decade [44]. PTC systems with a total of 354MW operational in California since the 1980s were made up of by a 14 MW electric plant, six 30 MW electric plants, and two latest 80 MW plants [45]. Costs of PTC systems ranging from US$ 0.12 to 0.14 $kWh^{-1}$ have been demonstrated commercially [44]. Additionally, a 64MW PTC system is under construction near Boulder city of Nevada and aims to reduce the cost of electricity from advanced solar technologies to US$ 0.05–0.10 $kWh^{-1}$, which is equivalent to the current cost of grid electricity [2]. Reliable high-temperature circulating pumps are critical to the success of the plants, and significant engineering effort has gone into assuring that pumps will stand the high-temperature cycling fluid. Because maintenance of high reflectance is critical to plant operation, tracking of the collectors is controlled by a system that utilizes an optimal system to focus radiation on sensitive sensors. Solar energy development policies in China can be divided into three administrative levels [41]. The policies of the first level are directive and outlined, and those of the second level are criterion policies. These policies are formulated by the central government and operated in the whole nation. These policies involve economic incentive policies, subsidy policies, tax remission policies and tariff favorable polices. To facilitate economic development by environment-friendly energy and to gain a higher value of direct normal insolation (DNI above 1800 $kWh/m^2a$) in large part of China, Chinese government supports the development of CSP technology strongly [46]. The third level policies are idiographic economic incentive policies regulated by local governments and approved of by central authorities. The data of solar and wind energy resources are put together with a variety of useful geographic and socio-economic information, such as the monthly averages for global and direct solar radiation, the seasonal and annual averages for global, diffuse, direct normal and latitude-tilted surface [47]. All available data are archived in geographic information system (GIS) format and can be used for decision-making as well as identifying potential areas for hybrid solar-wind power generation projects.

Power plants based on renewable sources face various difficulties mainly due to high costs and high uncertainties. A way to improve performance of these systems is to utilize more than one type of source to provide some degree of complementarities. Space complementarities may exist when the energy availabilities of one or more types of sources complement themselves over a certain region. Time complementarities may exist when the energy availability of one or more types of sources present periods of availability which are complementary over time in the same region [48]. For quite a long period of time, fossil-fueled generators were considered a necessary support to the operation of renewable source plants [44], but the use of more than one type of renewable source in the same energy system, such as wind and solar, has been seriously contemplated in the last few years [48]. Aspliden (1981) first examined the complementary nature of the wind and solar resource [49]. Artig (1995) subsequently studied time of day correlation between this combined resource and electrical demand [50]. The time-varying value of electricity using complementary nature of solar energy and wind power is significant because a large fraction of the solar resource is available at times of peak electrical load [31].

Even though generating electricity from renewable resources is a recommended alternative, it is difficult to find an optimal solution to simultaneously satisfy variant requirements from private associations, political groups, electric power companies, and local residents [51]. In addition, because of its great potential associated with high uncertainties, adopting conventional techniques such as cost analysis or profit analysis is impractical for the feasibility analysis of power generation system projects. Hence, this research proposes that an evaluation committee be established to analyze critical success factors and then an integrated framework be constructed to help analyze quantitative/qualitative, measurable/non-measurable, and positive/negative information and judgments. The committee is composed of nine members who have relevant professional knowledge about the projects being evaluated. The first duty of the committee is to find critical success criteria. Then, the feasibility analysis of the project under different sites with regards to benefits, opportunities, costs, and risks are evaluated based on market analysis, technical analysis, environmental and social impact assessment, and regulations. The outcome of the feasibility analysis is necessary for receiving approval from central authorities. Based on literature reviews and

practical experiences, the evaluation committee lists the following criteria to be the most important factors for solar-wind power generation projects. First, the factors under benefits are: solar-wind availability (monthly averages for global and direct solar radiation; annual averages for global, diffuse and direct solar radiation; mean wind power density; annual mean wind speed; degree of time and space complementarities), power generation functions (real and technical availability; reliability and efficiency; power factor and capacity factor), location advantage (influence of selected height of installation above ground; geomorphologic/hydrographical features; latitude-tilted surface). Second, the factors under opportunities are: policy support (subsidy policies; economic incentive policies; other policy supports), financial feature (tariff favorable polices; tax remission policies; other investment and production incentives), advanced technology (variable speed wind power generation; swept area of a turbine rotor; computerized supervisory system; new technologies to increase efficiency of PTC). Third, the factors under costs are: construction (the total preliminary construction expenditure of solar-wind power generation systems; peripheral facility construction expenditure), power generation systems (all expenditures on building up power generation systems including R&D, production, installation and maintenance), connection (electric connection, grid connection including the interconnection with distribution grid and transmission grid). Fourth, the factors under risks are: land use difficulty (difficulty in land purchase or lease agreement due to geology suitability, environmental protection, noise and aesthetics), technical uncertainty (technical complexity, uncertainties, and difficulties in the stages of R&D, manufacturing and installation), and interest conflict (conflicts among private associations, political groups, electric power companies, and local residents). These twelve critical success criteria and their sub-criteria, which are summarized in Table 1, are adopted in the subsequent real case study to select the best solar-wind power generation project.

## 4. Fuzzy analytic hierarchy process associated with BOCR

The analytic hierarchy process (AHP) is a simple, mathematically based multi-criteria decision-making tool to deal with complex, unstructured and multi-attribute problems [52]. The concept of benefits, opportunities, costs, and risks (the BOCR merits) can be incorporated into the AHP to facilitate the evaluation of a complex problem [53]. A hierarchy can consist of four sub-hierarchies, i.e., benefits, opportunities, costs and risks. Alternatives can be evaluated under these four aspects individually, and synthesized priorities of the alternatives can be further calculated. Fuzziness and vagueness are common characteristics in many decision-making problems, and good decision-making models should be able to tolerate vagueness or ambiguity. Thus, this paper presents a systematic fuzzy AHP model with BOCR. The steps are summarized as follows [9,54–56]:

**Step 1.** Form a committee of experts in the industry and define the solar-wind power generation system selection problem.

**Step 2.** Construct an evaluation framework for the problem. A control hierarchy, as depicted in the first part of Fig. 1, contains strategic criteria, the very basic criteria used to assess the problem, and the four merits, benefits (B), opportunities (O), costs (C) and risks (R). The control hierarchy is used to calculate the relative importance of the four merits. Next, decompose the problem into a BOCR hierarchy with four sub-hierarchies, as depicted in the second part of Fig. 1. Based on literature review and experts' opinions, a sub-hierarchy is formed for each of the four merits. For instance, for the sub-hierarchy for benefits (B) merit, there are criteria and sub-criteria that are related to the achievement of the benefits of the ultimate goal, and the lowest level contains the alternatives that are under evaluation.

**Table 1**
The criteria and sub-criteria for solar-wind generation projects.

| Merits | Criteria | Sub-criteria |
|---|---|---|
| Benefits | (a) Solar-wind availability | (a1) Solar irradiation of the area |
| | | (a2) Wind atlas of the area |
| | | (a3) Degree of time and space complementarities |
| | (b) Generation function | (b1) Real and technical availability |
| | | (b2) Efficiency and reliability |
| | | (b3) Power factor and capacity factor |
| | (c) Location advantage | (c1) Influence of selected height of installation |
| | | (c2) Geomorphologic/hydrographical features |
| | | (c3) Latitude-tilted surface |
| Opportunities | (d) Policy support | (d1) Subsidy policies |
| | | (d2) Economic incentive policies |
| | | (d3) Other policy supports |
| | (e) Financial feature | (e1) Tariff favorable polices |
| | | (e2) Tax remission policies |
| | | (e3) Other investment and production incentives |
| | (f) Advanced technology | (f1) Variable speed wind power generation |
| | | (f2) Swept area of a turbine rotor |
| | | (f3) Computerized supervisory system |
| | | (f4) New technologies to increase efficiency of PTC |
| | (g) Construction | (g1) Preliminary construction[a] |
| | | (g2) Peripheral construction[a] |
| Costs | (h) Power generation system | (h1) Design and development[a] |
| | | (h2) Production fee[a] |
| | | (h3) Installation and maintenance fee[a] |
| | (i) Connection | (i1) Electric connection[a] |
| | | (i2) Grid connection[a] |
| | (j) Land use difficulty | Difficulty in land purchase or lease agreement due to geology suitability, environmental protection, etc. |
| Risks | (k) Technical uncertainty | Technical complexity, uncertainties, and difficulties in the stages of R&D, manufacturing and installation |
| | (l) Interest conflict | Conflicts among private associations, political groups, electric power companies, and local residents |

[a] The value of each sub-criterion is the amount of cost needs to spend. The costs of sub-criteria under each cost criterion will be summed up for the evaluation.

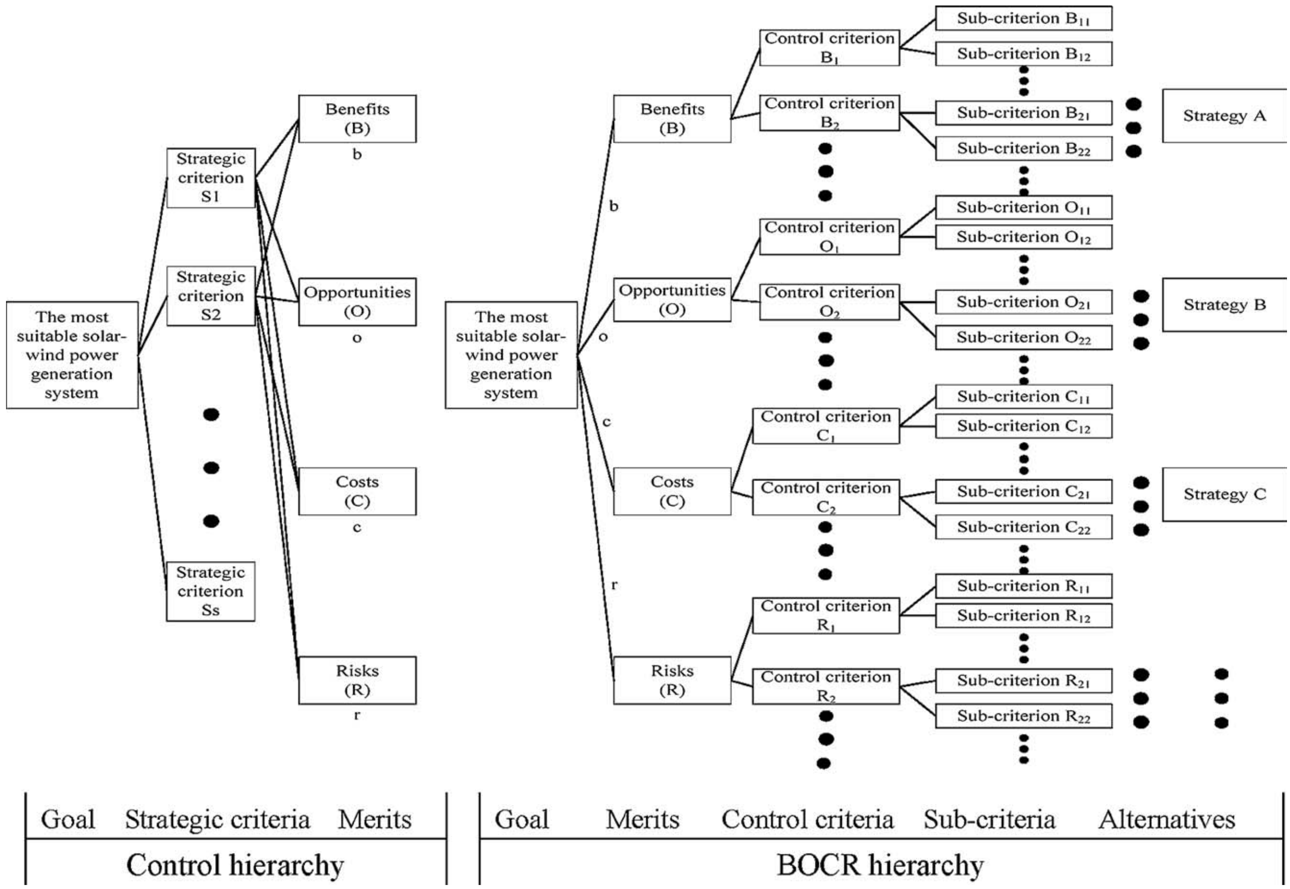



**Fig. 1.** The framework.

**Step 3.** Determine the priorities of the strategic criteria. Experts are asked to pairwise compare the strategic criteria toward achieving the overall objective. The scores of pairwise comparison of from each expert are transformed into linguistic variables by the transformation concept listed in Table 2. Form a pairwise comparison matrix for each expert, and geometric average approach is employed to aggregate experts' responses. A synthetic triangular fuzzy number $\tilde{r}_{ij}$ is resolved:

$$\tilde{r}_{ij} = (\tilde{a}_{ij1} \otimes \tilde{a}_{ij2} \otimes \ldots\ldots \otimes \tilde{a}_{ijk})^{1/k} \tag{1}$$

where $\tilde{a}_{ijk}$ is the pairwise comparison between strategic criteria $i$ and $j$ evaluated by expert $k$.

Defuzzy each triangular fuzzy number $\tilde{r}_{ij} = (l_{ij}, m_{ij}, u_{ij})$ into a crisp number $r_{ij}$ by the center of gravity method [57,58]. The aggregated pairwise comparison matrix is:

$$A = \begin{bmatrix} 1 & r_{12} & \cdots & \cdots & \cdots & \cdots & r_{1j} \\ 1/r_{12} & 1 & \cdots & \cdots & \cdots & \cdots & r_{2j} \\ \vdots & \vdots & 1 & \cdots & \cdots & \cdots & \cdots \\ \vdots & \vdots & \vdots & 1 & r_{ij} & \cdots & \cdots \\ \vdots & \vdots & \vdots & 1/r_{ij} & 1 & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots & \cdots & 1 & \cdots \\ 1/r_{1j} & 1/r_{2j} & \cdots & \cdots & \cdots & \cdots & 1 \end{bmatrix} \tag{2}$$

Derive priority vector for strategic criteria using the following equation [52]:

$$\mathbf{A} \cdot w = \lambda_{\max} \cdot w \tag{3}$$

The consistency property of the matrix is examined. If an inconsistency is found, experts are asked to revise the part of the questionnaire, and the calculation is done again.

**Step 4.** Determine the importance of benefits, opportunities, costs and risks to each strategic criterion. Obtain experts' opinions on the importance (impact) of the merit (B, O, C and R) on each strategic criterion by a five-point scale ($\tilde{1}, \tilde{3}, \tilde{5}, \tilde{7}, \tilde{9}$). The geometric average approach is used to aggregate experts' opinions, and the center of gravity method is applied to calculate the crisp importance of benefits, opportunities, costs and risks to each strategic criterion.

**Step 5.** Determine the priorities of the merits. Calculate the priority of a merit by multiplying the score of a merit on each strategic criterion from Step 4 with the priority of the respective strategic criterion from Step 3 and summing up the calculated values for the merit. Normalize the calculated values of the four merits, and obtain the priorities of benefits, opportunities, costs and risks, that is, b, o, c, r, respectively.

**Step 6.** Formulate a questionnaire based on the BOCR hierarchy to pairwise compare elements, or factors, in each level with respect to the same upper level element. For benefits (B) and opportunities (O), the question is to ask

**Table 2**
Membership functions of triangular fuzzy numbers.

| Fuzzy number | Linguistic variable | Membership function of fuzzy number |
|---|---|---|
| $\tilde{1}$ | Equally important | (1, 1, 3) |
| $\tilde{3}$ | Moderately important | (1, 3, 5) |
| $\tilde{5}$ | Important | (3, 5, 7) |
| $\tilde{7}$ | Very important | (5, 7, 9) |
| $\tilde{9}$ | Extremely important | (7, 9, 9) |

what gives the most benefit or presents the greatest opportunity to influence fulfillment of the criterion (sub-criterion). For costs (C) and risks (R), the question is to ask what incurs the most cost or faces the greatest risk. Experts in the field are asked to fill out the five-point scale questionnaire.

**Step 7.** Calculate the relative priorities in each sub-hierarchy. A similar procedure as in Step 3 is applied to establish relative importance weights of criteria with respect to the same upper level merit, the relative importance weights of sub-criteria with respect to the same upper level criterion, and the relative performance weights of alternatives with respect to each sub-criterion.

**Step 8.** Calculate the priorities of alternatives under each merit sub-hierarchy. The priorities of the alternatives under each merit are calculated by synthesizing the relative importance weights of criteria with respect to the same upper level merit, the relative importance weights of sub-criteria with respect to the same upper level criterion, and the relative performance weights of alternatives with respect to each sub-criterion.

**Step 9.** Calculate overall priorities of alternatives by synthesizing priorities of each alternative under each merit from Step 8 with corresponding normalized weights b, o, c and r from Step 5. There are five ways to combine the scores of each alternative under B, O, C and R [54,59].

1. Additive

$$P_i = bB_i + oO_i + c\left(\frac{1}{C_i}\right)_{\text{Normalized}} + r\left(\frac{1}{R_i}\right)_{\text{Normalized}}$$

where $B_i$, $O_i$, $C_i$ and $R_i$ represent the synthesized results of alternative $i$ under merit $B$, $O$, $C$ and $R$, respectively, and $b$, $o$, $c$ and $r$ are normalized weights of merit B, O, C and R, respectively.

2. Probabilistic additive

$$P_i = bB_i + oO_i + c(1 - C_i) + r(1 - R_i)$$

3. Subtractive

$$P_i = bB_i + oO_i - cC_i - rR_i$$

4. Multiplicative priority powers

$$P_i = B_i^b O_i^o \left[\left(\frac{1}{C_i}\right)_{\text{Normalized}}\right]^c \left[\left(\frac{1}{R_i}\right)_{\text{Normalized}}\right]^r$$

5. Multiplicative

$$P_i = \frac{B_i O_i}{C_i R_i}$$

## 5. A real case study

Selection of a suitable solar-wind power generation project in China should be implemented by feasibility analysis at the discretion of local circumstances. Then, the outcome of the feasibility analysis by the regional government is the instrument for receiving approval from central authorities. In order to examine the practicality of the proposed model, an anonymous province in China willing to select the most suitable solar-wind power generation project is used as an example. The project proposes the installation of nine PTC electric plants (a total of 564MW generating capacity) and 200 wind turbines (each with a generating capacity of 2.5MW). Taking three years to construct, the project is designed with an operational life of 30 years. In the first step of the evaluation process, a committee including three power entrepreneurs, two scholarly researchers, two legislative servants, two government officers was formed. Their first task was to select critical success criteria as described in Section 3. Then, based on literature reviews and practical experiences, the committee confirmed performance outcome, economic drivers and social needs are confirmed as the firm's strategic criteria. Fig. 2 shows the control hierarchy of the firm's overall performance. The second level includes the three strategic criteria. *Performance outcome* concerns the capabilities of the conversion system for delivering the results, such as availability, efficiency and complementarities, in variant processing conditions. *Economic drivers* are defined as the expectations of participants about the solar-wind power generation project, such as potentials and opportunities. *Social needs* concern whether the project possesses advanced technologies and new policies to satisfy social and economic needs. In the third level, four merits including benefits (B), opportunities (O), costs (C) and risks (R) are considered.

In the BOCR hierarchy, twelve selected criteria described in Section 3 are applied here to evaluate each solar-wind power generation project. Group factors (a), (b) and (c) are the criteria of *benefits* merit, and group factors (d), (e) and (f) are the criteria of *opportunities* merit. Under *costs* merit, there are three criteria, group factors (g) through (i). Under *risks* merit, there are three criteria, group factor (j) through (l). In the subsequent level, each criterion has its own sub-criteria as shown in Table 1. Five potential projects participated in the feasibility analysis are represented as alternative A, B, C, D, and E. Project A is located in the north-western region of the province. Project B is at the center region of the province. Project C and D are located in the southern and south-eastern coast respectively. Project E is at the eastern coast of the province.

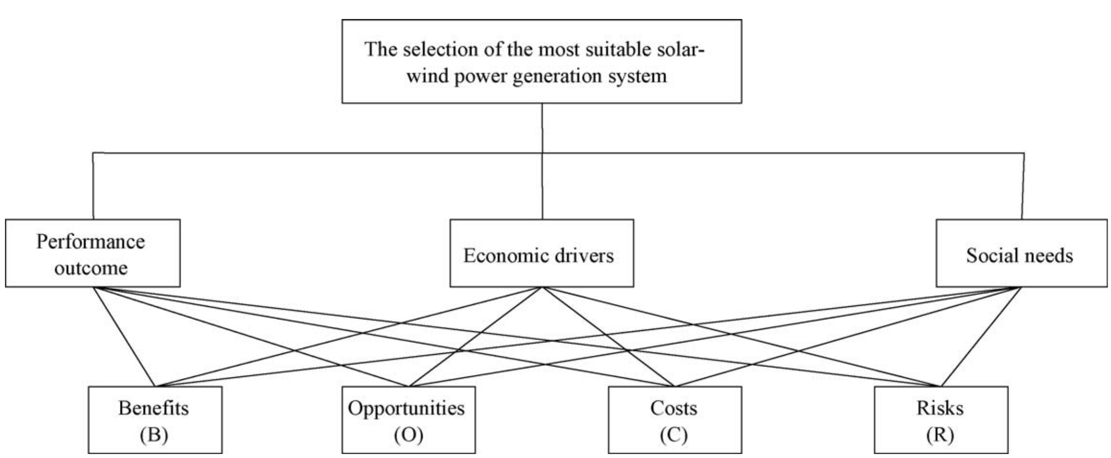



**Fig. 2.** The control hierarchy for solar-wind power generation system selection.

**Table 3**
Comparison matrix for the strategic criteria.

| | Performance outcome | Economic drivers | Social needs |
|---|---|---|---|
| Performance outcome | 1.0000 | 1.5135 | 1.8252 |
| Economic drivers | 0.6607 | 1.0000 | 0.7258 |
| Social needs | 0.5479 | 1.3778 | 1.0000 |

A questionnaire was constructed, and the members of the evaluation committee were invited to contribute their professional experience. Based on the collected opinions of the experts, the performance of the five projects can be generated.

In the first part of the model, experts were asked to evaluate the priorities of benefits, opportunities, costs and risks. The final pairwise comparison of the experts on the three strategic criteria with regards to the goal is as shown in Table 3.

An eigenvector is calculated using the eigenvalue method [52].

$$w_{s1} = \begin{matrix} \text{Performance outcome} \\ \text{Economic drivers} \\ \text{Social needs} \end{matrix} \begin{bmatrix} 0.4519 \\ 0.2535 \\ 0.2946 \end{bmatrix}$$

where $CI = 0.01942$ and $CR = 0.03348$ [52], the pairwise comparison matrix is consistent.

Next, experts were asked to assess BOCR according to strategic criteria by the five-step scale. The ratings of the four merits on strategic criteria are shown in Table 4. The normalized priorities of BOCR are calculated and shown in the last column of Table 4.

In the second part of the model, the priorities of the alternatives under each merit including benefits, opportunities, costs, and risks are calculated. The relative importance weights of criteria with regard to the same upper level merit and the relative importance weights of sub-criteria with regard to the same upper level criterion are calculated. The priorities of criteria and sub-criteria are shown in Table 5. Under the *benefits* merit, the most important criterion is *solar-wind availability*, with a very high benefit priority of 0.514. The most important sub-criterion is the *degree of time and space complementarities* with a benefit global priority of 0.230, followed by *solar irradiation of the area* (0.146) and *wind atlas of the area* (0.138). This means that the major benefit concern for the project is to have a stable and sufficient electric power from complementary solar energy and wind power for operation. Under the *opportunities* merit, both *economic incentive policies* (0.156) and *tax remission policies* (0.128) are the most important criteria. This implies that policy and financial supports are the most important drives to develop solar-wind power at present stage. Under the *costs* merit, the cost of *power generation systems* (0.575) is the major concern, followed by *connection* (0.302). Under the *risks* merit, *interest conflict* (0.469) and *land use difficulty* (0.349) are the problems the firm worries most about. This implies that the main problem to develop solar-wind project is the disparity among different parties. Note that even though there are sub-criteria under each *cost* criterion, the performances of a solar-wind project under these sub-criteria are estimated in monetary values. Therefore, no pairwise comparison of the importance of these sub-criteria is necessary since the values of the sub-criteria in a

**Table 4**
Priorities of benefits, opportunities, costs and risks.

| | Performance outcome (0.4519) | Economic drivers (0.2635) | Social needs (0.2946) | Priorities | Normalized priorities |
|---|---|---|---|---|---|
| Benefits | 0.3541 | 0.1438 | 0.1516 | 0.2411 | 0.2849 |
| Opportunities | 0.1728 | 0.2815 | 0.2024 | 0.2091 | 0.2470 |
| Costs | 0.2783 | 0.1767 | 0.1459 | 0.2135 | 0.2523 |
| Risks | 0.1146 | 0.2053 | 0.2672 | 0.1825 | 0.2157 |

**Table 5**
Relative priorities of criteria and sub-criteria.

| Merits | Criteria | Priorities | Sub-criteria | Local priorities | Global priorities |
|---|---|---|---|---|---|
| Benefits (0.2849) | (a) | 0.514 | (a1) | 0.285 | 0.146 |
| | | | (a2) | 0.268 | 0.138 |
| | | | (a3) | 0.447 | 0.230 |
| | (b) | 0.207 | (b1) | 0.429 | 0.089 |
| | | | (b2) | 0.384 | 0.079 |
| | | | (b3) | 0.187 | 0.039 |
| | (c) | 0.279 | (c1) | 0.345 | 0.096 |
| | | | (c2) | 0.259 | 0.072 |
| | | | (c3) | 0.396 | 0.110 |
| Opportunities (0.2470) | (d) | 0.382 | (d1) | 0.283 | 0.108 |
| | | | (d2) | 0.408 | 0.156 |
| | | | (d3) | 0.309 | 0.118 |
| | (e) | 0.324 | (e1) | 0.301 | 0.098 |
| | | | (e2) | 0.396 | 0.128 |
| | | | (e3) | 0.303 | 0.098 |
| | (f) | 0.294 | (f1) | 0.238 | 0.070 |
| | | | (f2) | 0.227 | 0.067 |
| | | | (f3) | 0.274 | 0.081 |
| | | | (f4) | 0.261 | 0.077 |
| Costs (0.2523) | (g) | 0.123 | a | | 0.123 |
| | (h) | 0.575 | a | | 0.575 |
| | (i) | 0.302 | a | | 0.302 |
| Risks (0.2157) | (j) | 0.349 | b | | 0.349 |
| | (k) | 0.182 | b | | 0.182 |
| | (l) | 0.469 | b | | 0.469 |

Note: a. The costs of sub-criteria under each cost criterion are summed up in the evaluation.
b. For criteria under the *risks* merit, there is no lower level sub-criterion.

**Table 6**
Priorities of alternatives under four merits.

| | Merits | | | |
|---|---|---|---|---|
| | Benefits (0.2849) | | Opportunities (0.2470) | |
| | Alternatives | | | |
| | Relative | Normalized | Relative | Normalized |
| Project A | 0.7852 | 0.1805 | 0.8786 | 0.1899 |
| Project B | 0.8716 | 0.2004 | 0.9071 | 0.1961 |
| Project C | 0.9313 | 0.2141 | 0.9521 | 0.2058 |
| Project D | 0.8629 | 0.1984 | 0.9339 | 0.2018 |
| Project E | 0.8985 | 0.2066 | 0.9551 | 0.2064 |

| | Merits | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Costs (0.2523) | | | | Risks (0.2157) | | | |
| | Alternatives | | | | | | | |
| | Relative | Normalized | Reciprocal | Normalized | Relative | Normalized | Reciprocal | Normalized |
| Project A | 0.8908 | 0.2132 | 4.6908 | 0.1872 | 1.0000 | 0.2492 | 4.0131 | 0.1568 |
| Project B | 0.8572 | 0.2051 | 4.8747 | 0.1946 | 0.9024 | 0.2249 | 4.4471 | 0.1737 |
| Project C | 0.7721 | 0.1848 | 5.4120 | 0.2160 | 0.5863 | 0.1461 | 6.8444 | 0.2674 |
| Project D | 0.8287 | 0.1983 | 5.0424 | 0.2012 | 0.8103 | 0.2019 | 4.9528 | 0.1935 |
| Project E | 0.8298 | 0.1986 | 5.0357 | 0.2010 | 0.7141 | 0.1779 | 5.6197 | 0.2195 |

**Table 7**
Final synthesis of priorities of alternatives.

| | Synthesizing methods | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Additive | | Probabilistic additive | | Subtractive | | Multiplicative priority powers | | Multiplicative | |
| | Alternatives | | | | | | | | | |
| | Priority | Rank | Priority | Rank | Priority | Rank | Priority | Rank | Priority | Rank |
| Project A | 0.1794 | 5 | 0.4589 | 5 | −0.0092 | 5 | 0.1789 | 5 | 0.6454 | 5 |
| Project B | 0.1921 | 4 | 0.4734 | 4 | 0.0053 | 4 | 0.1918 | 4 | 0.8517 | 4 |
| Project C | 0.2240 | 1 | 0.5016 | 1 | 0.0335 | 1 | 0.2229 | 1 | 1.6321 | 1 |
| Project D | 0.1989 | 3 | 0.4811 | 3 | 0.0129 | 3 | 0.1989 | 3 | 1.0001 | 3 |
| Project E | 0.2079 | 2 | 0.4894 | 2 | 0.0212 | 2 | 0.2078 | 2 | 1.2067 | 2 |

solar-wind project with regards to the same upper level criterion can simply be summed up into a single value. In addition, the experts agreed that there was no need for sub-criteria under the *risks* merit because criteria themselves can clearly express the risks that may be faced by the solar-wind projects.

The performance results of different solar-wind projects under various criteria were collected from each expert individually in order to limit the number of pairwise comparisons. Some sub-criteria under *costs* and *benefits* merits are quantitative and some are qualitative, and those under *opportunities* and *risks* merits are all qualitative. Each quantitative sub-criterion result given by expert is calculated by a set of optimistic data. Here is an example. The result of sub-criterion *wind atlas of the area* for each project is obtained from synthesizing the normalized data from true values of annual mean wind speed, means wind power density, and geographical distribution of wind speed frequency with suitable weights. However, the result from a qualitative sub-criterion, such as tariff favorable polices, is obtained from each expert's subjective evaluation on factors such as equipment tariff, switchable tariff, and operations tariff and then a value from one to a hundred is assigned. Actually, the higher the score for the criteria under *benefits* and *opportunities* merits, the better the performance of the project is. Oppositely, the higher the value for the criteria under *costs* and *risks* merits, the worse the performance of the project is. The performance value of each project on each criterion is calculated by synthesizing the results from all the experts by the arithmetic average method. These performance values are further transformed into a number between zero to one by dividing the performance value of a project on a criterion by the largest performance value among all projects on the same criterion. The above performance values of projects and the priorities of criteria are synthesized to obtain the overall performance of each project under each merit. The normalized performances of projects under the four merits are calculated as shown in Table 6.

The final ranking of the alternatives are calculated by the five methods to combine the scores of each alternative under B, O, C and R. The results are as shown in Table 7. Under all five methods of synthesizing the scores of alternatives, the ranking is exactly the same in sequence: Project C, E, D, B and A. However, note that the ranking under the five methods may be different depending on the case. Project C is expected to be the best project mainly because it has the best performance under three out of the four merits, that is, the project performs the best under the benefits merit, and is the least costly and least risky among all the project. Even though Project C ranks the second under the opportunities merit, its better performance under the other merits guarantees its first rank under the synthesizing methods. Project E ranks the second overall. Although it ranks the first under the opportunities merit, it ranks the second under the benefits and risks merits, and ranks the third under the costs merit. Also note that project A should not be selected since it has a negative priority under the subtractive method.

## 6. Conclusion and discussion

There is no doubt that the move toward generating electricity from renewable resources will become the main trend in recent years. A solar-wind power generation system has a very high power-generating potential because of the complementariness

between solar and wind resources. However, no solid mathematically based model has been proposed before on the evaluation and selection of the systems. With the increasing complexity in social environments along with rapidly changing technologies, integrating critical factors of solar-wind power generation systems including market, technologies, social and environmental impacts can facilitate the evaluation process. From the process of analyzing critical factors, we find that some of the factors like policy support, new technologies, and financial mechanisms do accelerate opportunities of adopting solar-wind power generation systems. However, some factors like uncertainties of land usage and new technologies, and the disparity among different parties, have negative impacts. In order to handle positive and negative criteria, AHP with BOCR is proposed to facilitate the strategic selection of solar-wind power generation projects. In addition, in order to handle imprecise and vague experts' judgment, a fuzzy set theory is also applied to the aforementioned model. Finally, from our theoretical modeling and empirical demonstration, a fuzzy AHP with BOCR model can effectively and precisely handle such a complicated problem and lead to an outstanding result.

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